NAVAL POSTGRADUATE SCHOOL

MONTEREY, CALIFORNIA

THESIS

THE NEXT GREAT ENGINE WAR: ANALYSIS AND RECOMMENDATIONS FOR MANAGING THE JOINT STRIKE FIGHTER ENGINE COMPETITION

by

Karl G. Amick

December 2005

Principal Advisor:	Albert F. Bodnar
Associate Advisor:	Walter E. Owen

Approved for public release; distribution is unlimited.

THIS PAGE INTENTIONALLY LEFT BLANK

REPORT DOCUMENTATION PAGE	*Form Approved OMB No. 0704-0188*

1. AGENCY USE ONLY *(Leave blank)*	**2. REPORT DATE** December 2005	**3. REPORT TYPE AND DATES COVERED** Master's Thesis

4. TITLE AND SUBTITLE: The Next Great Engine War: Analysis and Recommendations for Managing the Joint Strike Fighter Engine Competition	**5. FUNDING NUMBERS**
6. AUTHOR(S) Karl G. Amick	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Naval Postgraduate School, Monterey, CA 93943-5000	**8. PERFORMING ORGANIZATION REPORT NUMBER**
9. SPONSORING /MONITORING AGENCY NAME(S) AND ADDRESS(ES) N/A	**10. SPONSORING/MONITORING AGENCY REPORT NUMBER**

11. SUPPLEMENTARY NOTES The views expressed in this thesis are those of the author and do not reflect the official policy or position of the Department of Defense or the U.S. Government.

12a. DISTRIBUTION / AVAILABILITY STATEMENT Approved for public release; distribution is unlimited.	**12b. DISTRIBUTION CODE**

13. ABSTRACT (maximum 200 words)

This research evaluates the Joint Strike Fighter (JSF) Program acquisition of Pratt & Whitney (P&W) F135 and the General Electric Aircraft Engines/Rolls Royce (GEAE/RR) F136 engines. This study examines existing research on the first 'Great Engine War'.

The first Great Engine War was an attempt by the Government to encourage Pratt & Whitney, the sole winner of the F-16 fighter engine propulsion contract, to be more responsive to shortcomings in design and support. When P&W declared that any design changes would be out of the scope of the current contract, the government contracted with GEAE to produce an alternate engine design to compete against P&W. The competition was a success.

The study also includes Interviews with veterans of the Great Engine War. The findings are balanced against the current JSF acquisition planning to ensure applicability.

The research and analysis yielded the following recommendations to guide the JSF future engine acquisition: ensure airframe commonality for both engines, continue to purchase and support the engines as Government-Furnished Equipment (GFE), utilize supportability costs as competition criteria, maintain a concerted effort to encourage both competitors to attempt to win the maximum share, and do not participate in a Component Improvement Program.

14. SUBJECT TERMS Propulsion competition, Great Engine War, Component Improvement Program (CIP)	**15. NUMBER OF PAGES** 77
	16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	**18. SECURITY CLASSIFICATION OF THIS PAGE**	**19. SECURITY CLASSIFICATION OF ABSTRACT**	**20. LIMITATION OF ABSTRACT**
Unclassified	Unclassified	Unclassified	UL

NSN 7540-01-280-5500 Standard Form 298 (Rev. 2-89) Prescribed by ANSI Std. 239-18

THIS PAGE INTENTIONALLY LEFT BLANK

Approved for public release; distribution is unlimited.

THE NEXT GREAT ENGINE WAR: ANALYSIS AND RECOMMENDATIONS FOR MANAGING THE JOINT STRIKE FIGHTER ENGINE COMPETITION

Karl G. Amick
Civilian, Naval Air Warfare Command – Aircraft Division, United States Navy
B.S., Embry Riddle Aeronautical University, 1992

Submitted in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE IN PRODUCT DEVELOPMENT

from the

NAVAL POSTGRADUATE SCHOOL
December 2005

Author:	Karl G. Amick
Approved by:	Albert F. Bodnar Principal Advisor
	Walter E. Owen, DPA Associate Advisor
	Frank Shoup, Ph.D. Director, Wayne E. Meyer Institute for System Engineering

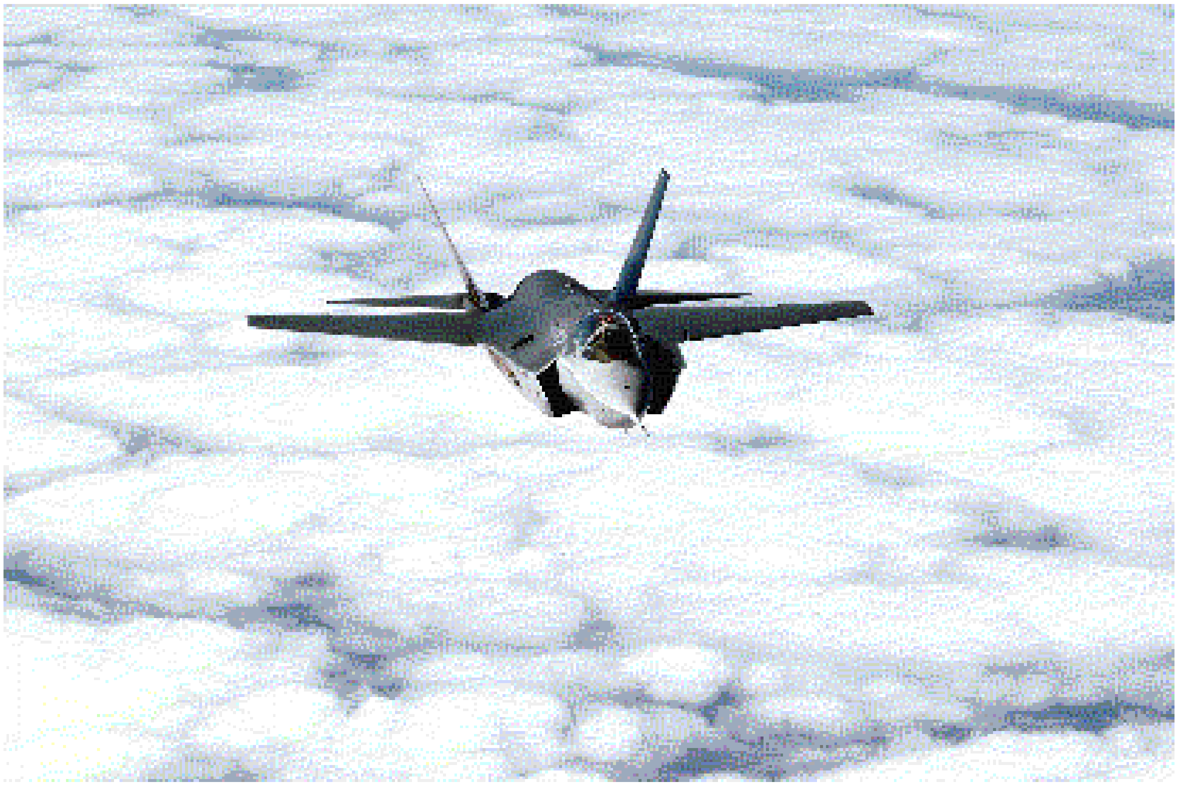

Figure 1. F-35 Prototype

ABSTRACT

This research evaluates the Joint Strike Fighter (JSF) Program acquisition of Pratt & Whitney (P&W) F135 and the General Electric Aircraft Engines/Rolls Royce (GEAE/RR) F136 engines. This study examines existing research on the first 'Great Engine War'.

The first Great Engine War was an attempt by the Government to encourage Pratt & Whitney, the sole winner of the F-16 fighter engine propulsion contract, to be more responsive to shortcomings in design and support. When P&W declared that any design changes would be out of the scope of the current contract, the government contracted with GEAE to produce an alternate engine design to compete against P&W. The competition was a success.

The study also includes Interviews with veterans of the Great Engine War. The findings are balanced against the current JSF acquisition planning to ensure applicability.

The research and analysis yielded the following recommendations to guide the JSF future engine acquisition: ensure airframe commonality for both engines, continue to purchase and support the engines as Government-Furnished Equipment (GFE), utilize supportability costs as competition criteria, maintain a concerted effort to encourage both competitors to attempt to win the maximum share, and do not participate in a Component Improvement Program.

Figure 2. Joint Strike Fighter (Artist Concept)

TABLE OF CONTENTS

THIS PAGE INTENTIONALLY LEFT BLANK

LIST OF FIGURES

THIS PAGE INTENTIONALLY LEFT BLANK

LIST OF TABLES

ACKNOWLEDGMENTS

I would like to gratefully acknowledge the assistance of Mr. Al Bodnar (Deputy Director for Autonomic Logistics, Joint Strike Fighter Program) for his encouragement and willingness to lend his expertise to this study.

My thesis advisor, Dr. Wally Owen, as well as the staff at the Naval Postgraduate School, has been tremendous to work with and given me the confidence to reach for success.

Another key person in this journey has been Mr. Sonny Fann, who supported and encouraged me in meeting the demands of school and work to achieve my degree.

I am grateful for the support and guidance from my wife, Jackie, and my two sons.

This acknowledgment can not be complete without mentioning Mr. Ken Kohrs, who survived the first Great Engine War and will be key to the success of the *Next Great Engine War*.

I. INTRODUCTION

A. PURPOSE

The purpose of the study is to research and evaluate the F-16 Great Engine War and derive recommendations which will guide Joint Strike Fighter Engine Program competition between Pratt & Whitney (P&W) and the General Electric Aircraft Engines/Rolls Royce (GEAE/RR) Fighter Engine Team. The objective is to gather the different viewpoints and identify the opportunities and challenges of this ongoing competition between two large companies for a large stake in the future of military aviation for the next 40 years.

B. SCOPE AND METHODOLOGY

The scope of this paper encompasses a detailed review of the current literature on the first great engine war and F-16 propulsion acquisition. Included is the most recent acquisition strategy for the *Joint Strike Fighter* program drawn from unclassified sources and publicly disseminated information. Detailed interviews were performed with key stakeholders from the F-16 engine acquisition and Joint Strike Fighter Program. The interviews were studied using qualitative analysis to understand motives and to derive the recommendations.

C. BACKGROUND

1. The First Great Engine War

The first ‘Great Engine War’ was born of the engine acquisition for the new US Air Force (USAF) lightweight fighter, the F-16 *Fighting Falcon.* The engine from the F-15 *Eagle* was selected to power the nimble aircraft. However, there were reliability problems with the Pratt & Whitney (P&W) F100 engine powering the F-15. In F-15 operational use and early in the F-16 flight test program the engine experienced compressor stall problems and higher than anticipated turbine blade fatigue. P&W was reluctant to resolve these issues under the scope of current contract. The P&W stance was that the failures were pilot-

induced. The company requested more funding from the government to fix the problems for the Air Force. To improve contractor responsiveness and reduce operational risk, the USAF sought another source of fighter engines.

Figure 3. YF-16 Prototype (F-16.Net, 2005)

The government proceeded to contract with General Electric Aircraft Engines (GEAE) to build a suitable engine to compete with the F100 for F-16C/D Block 30 aircraft acquisition. The GEAE F110-GE-220 engine was successful and the competition did motivate P&W to improve their engine design as well.

2. F-16 Program Description

The F-16 has been a highly successful fighter aircraft program. The *Fighting Falcon* is operated by the US Air Force and many allied nations. It has

been instrumental in many victories including the recent Global War on Terrorism. Global Security.Org is an excellent source for the history of the F-16:

> The air war experience in Vietnam highlighted the lack of maneuverability of USAF F-4 *Phantom II* fighters at transonic speeds. This provided advantages to nimble enemy fighters and became the stimulus for the Lightweight Fighter program.
>
> The Air Force and designers of the Lightweight Fighter therefore placed great emphasis on achieving unprecedented transonic maneuver capability with excellent handling qualities.
>
> In January 1972, the Lightweight Fighter Program solicited design specifications from several American manufacturers. Participants were told to tailor their specifications toward the goal of developing a true air superiority lightweight fighter. General Dynamics (GD) and Northrop were asked to build prototypes, which could be evaluated with no promise of a follow-on production contract. These were to be strictly technology demonstrators. The two contractors were given creative freedom to build their own vision of a lightweight air superiority fighter, with only a limited number of specified performance goals. Northrop produced the twin-engine YF-17, using breakthrough aerodynamic technologies and two high-thrust engines. General Dynamics countered with the compact YF-16, built around a single P&W F100 engine.
>
> The evolution of the YF-16 design included studies of configuration variables such as wing design, maneuvering devices, number and location of engines, control surfaces, number and location of tail surfaces, and structural concepts. As the configuration options matured, two candidate configurations competed for priority. The first configuration was a simple wing, body, and empennage design, while the second design was a twin-tailed, blended-wing body with vertical and horizontal tails on booms. The team selected the best features of both configurations for the final YF-16 design.

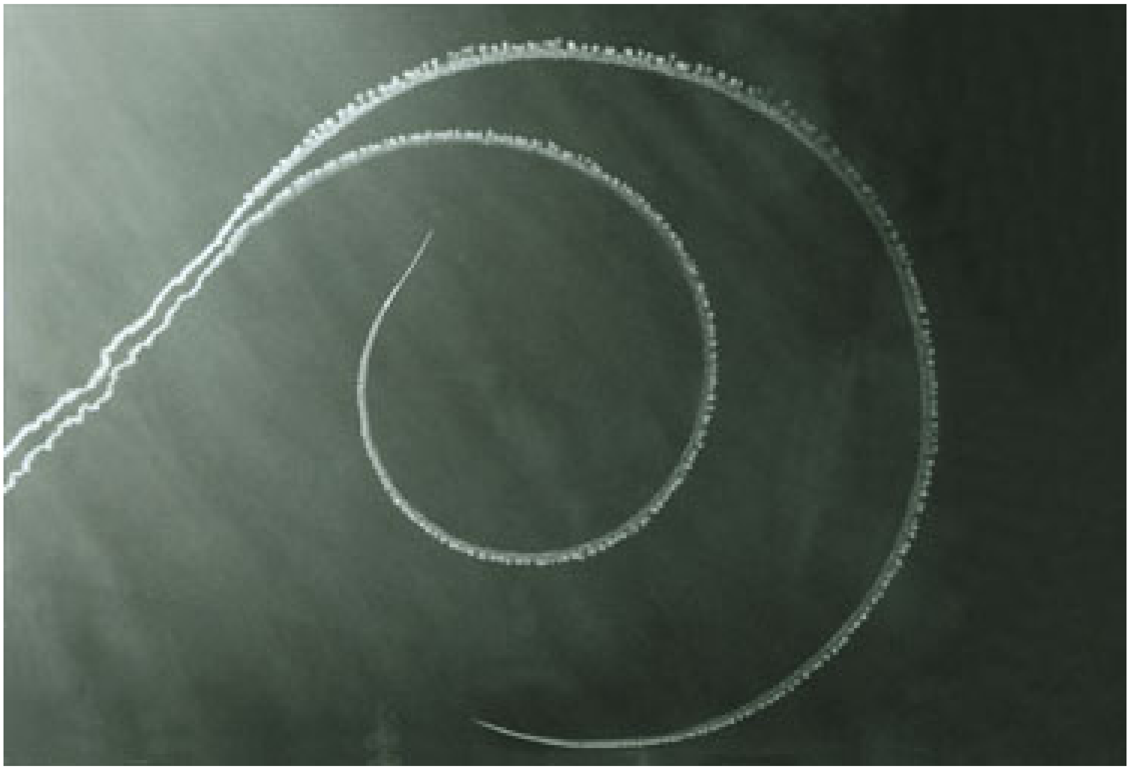

Figure 4. An F-16 demonstrates its remarkably tight turning radius against an F-4E (Nederveen, 2004)

Increased maneuverability for the YF-16 necessitated extended flight at high angles of attack where aerodynamic deficiencies caused by separated airflow can result in sudden decreases in stability and controllability. Therefore, special emphasis was placed on tests to insure that the YF-16 could provide the pilot with “care-free” maneuverability. To provide superior handling characteristics at high angles of attack, any undesirable handling characteristics were pushed out of the operating envelope of the aircraft and the flight envelope was limited with an advanced fly-by-wire flight control system by design. This concept has proven to be highly successful and has been used in all variants of the F-16.

When the Lightweight Fighter competition was completed early in 1975, both the YF-16 and the YF-17 showed great promise. The two prototypes performed so well, in fact, that both were selected for military service[1]. On 13 January 1975 the Air Force announced that the YF-16's performance had made it the winner of its Air Combat Fighter (ACF) competition. This marked a shift from the

[1] The YF-17 soon became the USN F/A-18 *Hornet*.

> original intention to use the two airplanes strictly as technology demonstrators. General Dynamics' YF-16 had generally shown superior performance over its rival from Northrop. At the same time, the shark-like fighter was judged to have production costs lower than expected, both for initial procurement and over the life cycle of the plane. At the same time, the YF-16 had proved the usefulness not only of fly-by-wire flight controls, but also such innovations as reclined seat backs and transparent head-up display (HUD) panels to facilitate high-G maneuvering, and the use of high profile, one-piece canopies to give pilots greater visibility. Thus, the Air Force had its lightweight fighter, the F-16. (Global Security, 2005)

On December 9, 1992, Lockheed bought out the Fort Worth Division of General Dynamics for $1.525B in cash. The plant would now operate as the Lockheed Fort Worth Company. This marked the end of production of complete aircraft by General Dynamics.[2] The manufacture of the F-16 would, however, still continue at Fort Worth, with the aircraft now being known as the *Lockheed* F-16.

Foreign countries also were licensed to assemble airframes and engines. The F-16 Fighting Falcon continues its historic evolution, honing its edge in meeting new operational requirements both in the defense marketplace and in combat, according to John Bean, Vice President for Lockheed Martin F-16 programs (Brannan, 2003):

> [The] F-16 is still the most modern, capable and sought-after international production fighter today. It has been proven in combat time after time, including recent operations in Bosnia, Kosovo, Afghanistan and both wars in Iraq.
>
> "The F-16 international family marks its 25th anniversary this year," Bean said. "Since 1979, partnerships with our allies and coalition countries have grown to 24, including the United States. And we have every reason to believe that our international family will continue to grow. With a win rate of 100 percent in competitions for authorized programs, the F-16 proves time and again it is the world's most sought-after fighter jet."

[2] , the remaining elements of the company now being involved only in the manufacture of submarines, the M1A1 tank, airliner components, missiles, space systems, and electronics.

> The F-16 is the choice of 24 countries. More than 4,000 aircraft have been delivered, hundreds more are on order, and production is expected to continue beyond 2010. Major upgrades for all F-16 versions are being incorporated to keep the fleet modern and fully supportable over the aircraft's long service life.

F-16 production continued with each successive design improvement grouped into 'blocks'. The F-16A/Bs ended with Block 20. The F-16C/Ds begin with Block 25 and continue through Block 50/52. There have also been many design variants to test different wings, flight control schemes, and engine nozzles.

The last F-16s produced will be the FMS-only Block 60 (F-16E/F) *Desert Falcon* produced for the United Arab Emirates (UAE). The Block 60s will have the following features, (which set it apart from the most modern Block 50 F-16s in the US Air Force inventory):

- Conformal fuel tanks mounted above the wing root, which allow for a mission radius of 1,025 miles with no in-flight refueling. This amounts to a 40 percent increase over the range of the current Block 50 F-16.

- Internal forward-looking infrared targeting system mounted into the nose of the aircraft, which replaces the external pods on earlier F-16 models. This reduces drag and lowers the radar cross section of the aircraft, making detection by the enemy more difficult.

- Agile-beam radar, which employs an active, electronically scanned antenna to achieve the wide bandwidth necessary to support the Desert Falcon's mission. The radar relies on a fixed panel of transmitters and receptors that can broadcast beams quickly and in every direction.

- Electronic countermeasures suite with internal electronic countermeasures and an electronic-warfare management system designed to foil Russian double-digit surface-to-air missiles such as the SA-10 and SA-12.

- Advanced mission computer to enhance sensor and weapon integration.

- Three five-inch by five-inch color displays in the cockpit and a helmet-mounted cueing system to improve situational awareness of the pilot. (Nederveen, 2000)

3. Pratt & Whitney F100 Engine Description

Because Pratt & Whitney powered the prototype YF-16 (with the P&W F100 engine from the F-15) they were naturally selected to power the winning General Dynamics aircraft design.

Pratt & Whitney and the U.S. Air Force initiated development of the F100-PW-220 specifically for the F-16. It was similar to the F-15 engine, but featured an increased life core section, a digital electronic engine control, a gear-type fuel pump, improved augmenter, and an engine diagnostics unit.

The F100-PW-100 for the F-15 was an extremely innovative engine that pushed the boundaries of contemporary technology, especially in the area of exotic high-temperature materials. A tight Air Force schedule and budget left little room for dealing with the inevitable technical problems, schedule slippage, and cost growth. In June 1971, the Navy pulled out of the program because of continuing technical development problems, dramatically increasing the program costs for the Air Force.

Figure 5. F100-PW-220

Not only did development problems continue through full scale development and flight testing, but the engine went into production before

development was completed. Fixes done under government-funded Component Improvement Programs continued after the engine entered service with the F-15 in late 1974. The engine was extremely powerful and capable but continued to experience severe operational and reliability problems. The F100 engine was so powerful and the F-15 so maneuverable that pilots began pushing the aircraft to the edge of the performance envelope in ways that stressed the engine far more than had been anticipated. These stresses resulted in much worse reliability and maintenance problems than were originally expected. In addition, new heavy-maneuvering air-to-air combat tactics developed by Air Force pilots revealed another problem: compressor stall caused by strong dynamic airflow distortion in the engine inlet. Severe compressor stall could lead to engine flame out, requiring the pilot to restart the engine in flight. This problem caused particular concern because the F100 was planned for use on the single-engine General Dynamics F-16 as well as on the dual-engine F-15 (Baugher, 2000):

> When it first flew, the YF-16 seemed to be almost free of the stagnation stall problems which had bedeviled the F-15. However, while flying with an early model of the F100 engine, one of the YF-16s did experience a stagnation stall, although it occurred outside the normal performance envelope of the aircraft. Three other incidents later occurred, all of them at high angles of attack during low speed flights at high altitude. The first such incident in a production F-16 occurred with a Belgian aircraft flying near the limits of its performance envelope. Fortunately, the pilot was able to get his engine restarted and land safely. The F-16 was fitted with a jet-fuel starter, and from a height of 35,000 feet the pilot would have enough time to attempt at least three unassisted starts using ram air.
>
> When the F100 engine control system was originally designed, Pratt & Whitney engineers had allowed for the possibility that the ingestion of missile exhaust might stall the engine. A "rocket-fire" facility was designed into the controls to prevent this from happening. When missiles were fired, an electronic signal was sent to the unified fuel control system which supplied fuel to the engine core and to the afterburner. This signal commanded the angle of the variable stator blades in the engine to be altered to avoid a stall, while the fuel flow to the engine was momentarily reduced and the afterburner exhaust was increased in area to reduce the magnitude

of any pressure pulse in the afterburner. Tests had shown that this "rocket-fire" facility was not needed for its primary purpose of preventing missile exhaust stalls, but it turned out to be handy in preventing stagnation stalls. Engine shaft speed, turbine temperature, and the angle of the compressor stator blades are continuously monitored by a digital electronic engine control unit which fine-tunes the engine throughout flight to ensure optimal performance. By monitoring and comparing spool speeds and fan exhaust temperature, the unit is able to sense that a stagnation stall is about to occur and send a dummy "rocket-fire" signal to the fuel control system to initiate the anti-stall measures described above. At the same time, the fuel control system reduces the afterburner setting to help reduce the pressure within the jetpipe.

The afterburner-induced stalls were addressed by a different mechanism. In an attempt to prevent pulses from coming forward through the fan duct, a "proximate splitter" was developed. This is a forward extension of the internal casing which splits the incoming air from the compressor fan and passes some of this air into the core and diverts the rest down the fan duct and into the afterburner.

By closing the gap between the front end of this casing and the rear of the fan to just under half an inch, the designers reduced the size of the path by which high-pressure pulses from the burner had been reaching the core. Engines fitted with the proximate splitter were tested in the F-15, but this feature was not introduced on the F-15 production line, since the loss of a single engine was less hazardous in a twin-engined aircraft like the Eagle. However, this feature was adopted for the single-engined F-16.

These engine fixes produced a dramatic improvement in reliability. Engines fitted to the F-16 fleet (and incorporating the proximate splitter) had only 0.15 stagnation stalls per 1000 hours of flying time, much better than the F-15 fleet.

There were other problems associated with the F100 engines. The down-stream effects of the stresses of the design affected internal component life also.

The compressor stall problem also contributed to another major shortcoming—turbine blade fatigue and failures that had the potential of destroying the aircraft in flight. To avoid potentially catastrophic accidents, performance limitations were placed on pilots, and mechanics had to de-rate the

life of the engine (Younossi, O., Arena, M., Moore, R., Lorell, M., Mason, J., & Grasser, J., 2002).

The Air Force turned to P&W to fix these problems under the existing contract. P&W argued that it had delivered an engine that met the original performance specifications. The problem, according to P&W, was that the Air Force pilots began operating the engine in a much more demanding environment than had originally been specified. Therefore, P&W argued that the Air Force should provide additional developmental money to fix the problems. (Baugher, 2000)

4. General Electric Aircraft Engine F110 Description

In 1984 the Department of Defense awarded General Electric Aircraft Engines (GEAE) a contract to build a small number of F101 Derivative Fighter Engines (DFE) for flight test[3]. The DFE was based on the F101 used in the B-1 aircraft but incorporated components derived from the F404 engine used in the F/A-18. The tests were very successful and showed the feasibility of the alternate engine.

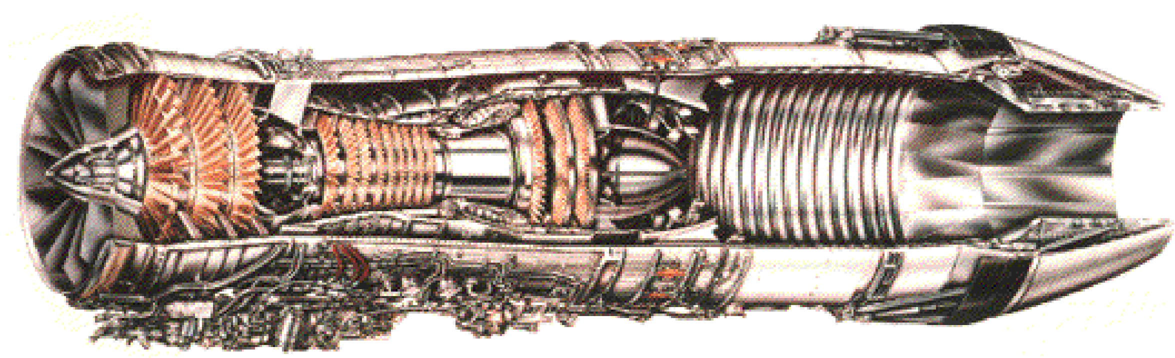

Figure 6. F110-GE-100

[3] The Navy later decided to adopt the DFE as a replacement for the F-14 *Tomcat* P&W TF30 turbofan.

The GEAE F110-GE-100 is a dual-rotor augmented turbofan engine in the 27,000 lb. thrust class. The parts of the F110 core[4] are 92% common to the F101 and 60% common to the F108 (for the USAF KC-135 *Stratotanker*). The low pressure turbine and augmentor are scaled from the F101 engine. The F110 also has a scaled up inlet fan and exhaust nozzle from the F404 engine. (Hoover, 1986, p. 3)

Moreover, the F110 design was kept conservative with no cutting edge materials or design practices. This allowed high maturity and confidence in the design when production started.

At the time of its introduction in December 1985, this core had accumulated more than 3.5 million hours of ground test, flight test, and operational flight hours (Hoover, 1986, p. 3). This greatly reduced risk for the alternate engine and helped speed its introduction.

5. F-16 Engine Competition (“The Great Engine War”)

As a result of the Pratt & Whitney situation, the USAF became interested in acquiring an alternative engine for the F-16C/D. The goal was to convince P&W to address the problems inherent to their design because the Government *could* have another source for engines. The challenge to the sole-source situation would change P&W corporate responses.

The development of a source for an alternate engine for the Navy's F-14 Tomcat gave the Government just such an opportunity to challenge Pratt & Whitney.

On 5 March 1979, the Air Force contracted with GEAE for initial development of an F101 derivative from the B-1 program for F-16 use. GEAE’s task was to put an engine in the F-16 and fly it successfully before 30 months had elapsed. (Drewes, 1987, p. 98)

---

[4] Defined as the fan through exhaust frame, comprising most of the engine less the augmentor and exhaust nozzle sections

The P&W response to a proposed competition was not to try harder to please the customer, i.e. the USAF, rather they attempted to get Congress to force the customer to abandon the alternate engine competition.

Because the availability of money was the key element for success of the Air Force strategy, P&W chose to fight the GEAE engine alternative at the source of the money, Capitol Hill. In February and March of 1979, a series of thorough, intensely debated Congressional hearings were held on Air Force intentions toward the F100 and a GEAE alternative. Leading the charge for P&W was the Connecticut delegation, particularly Congressman Giamo, in hearings that became a forum for venting all of P&W’s concerns. (Drewes, 1987, p. 100)

These corporate tactics only increased the resolve of the US Air Force to proceed with the competition. The development of a successful alternate engine continued. In the end, the USAF leadership prevailed and authorized the F-16 System Program Office (SPO) to release the Request for Proposal (RFP) to both engine companies.

All F110s ordered by the USAF were for the F-16 fleet, with the F-15 retaining the F100. The choice of engines for the F-16 began with the Fiscal Year 1985 Block 30 F-16C/Ds.

The GEAE engine proposal was a success and actually won 57% of the first year competition, 54% in the second year, and 56% in the third year. Pratt regrouped and was able to win 55% in the fourth year, 57% in the fifth year of the competition (Leginus, 1998, p. 22)

Figure 7. Block 30 F110-GE-100

Figure 8. Block 32 F100-PW-220

It was never intended that individual squadrons or wings would operate with a mixed fleet of F-16s powered by two different engine types, since that would create a spare parts and logistics nightmare.

The F-16C/D Block 30 aircraft (see Figure 7.) was the first airframe introduced with the GEAE F110-GE-100 engine as a powerplant option.

The F-16C/D Block 32 airframes (see Figure 8.) were powered by the F100-PW-220 engine. In spite of the so-called Common Engine Bay, the two

powerplants are not interchangeable (Fieser, 2003). Each Block of aircraft could only ever have the applicable F100 or F110 installed.

In an attempt to make the F100 more competitive with the GEAE F110, Pratt & Whitney introduced the more powerful F100-PW-229 version in the early 1990s. This engine is rated at 29,100 pounds of thrust with full afterburner. It has higher fan airflow and pressure ratio, higher-airflow compressor with an extra stage, new float-wall combustor, higher turbine temperatures, and a redesigned afterburner. It has about 22 percent more thrust than previous F100 models. The first F-16s powered by the -229 engines began to be delivered in 1992. However, the degree of mechanical changes introduced in the -229 made it impractical to rebuild -200 or -220E engines to -229 standards.

On the export market, the higher thrust of the F110 made it the engine of choice through the mid to late 1980s. The more powerful F100-PW-229 finally gave P&W the chance of re-entering the export market. In 1991, South Korea chose the F100-PW-229 for its license-built F-16s.

The F100-PW-200+ is intended for foreign air forces which operate significant numbers of F-16s that are powered by -200 and -220E engines, but which are denied access to the more powerful -229. It combines the core of the -220 with the fan, nozzle, and digital control system of the -229. It develops around 27,000 pounds of thrust with afterburning.

6. Joint Advanced Strike Technology (JAST) Program

The JAST Program was created to explore ways to affordably meet a shortfall in our fighter force for a new multi-role fighter. The JAST program began when the 1993 Bottom-Up Review (BUR) determined that a separate tactical aviation modernization program by each Service was not affordable and discontinued the Multi-Role Fighter (MRF) and Advanced Strike Aircraft (A/F-X) studies.

Figure 9. F-35B Short Take Off/Vertical Land (STOVL)

In 1994 the Common Affordable Lightweight Fighter (CALF) was integrated into JAST as well. The CALF Advanced Short Take Off/Vertical Land (ASTOVL) concepts were originally seen as developing a replacement for the U.S. and U.K. Harrier jump-jet. The ASTOVL concepts became multi-service with the planning of multiple variants.

The management of the CALF program was handled by the Defense Advanced Research Projects Agency (DARPA) due to the experimental nature of the concept. The CALF program goal was to develop the technologies and concepts to support the ASTOVL aircraft for the USMC and Royal Navy (RN) and a highly-common conventional flight variant for the U.S. Air Force (JSF Public Affairs, *CALF Description*, p.1).

Figure 10. JAST Logo

After a DoD review of the program in August 1995, the JSF program emerged from the JAST effort. Fiscal Year 1995 legislation merged the DARPA ASTOVL program with the JSF Program. This action drew the United Kingdom (UK) Royal Navy into the program, extending a collaboration begun under the DARPA ASTOVL program. (Federation of American Scientists, 2005)

7. Joint Strike Fighter (JSF) Program Description

The JSF will meet the need to be capable of meeting the current and future needs of the USAF, USN, USMC and partner countries to affordably and effectively replace such existing systems as the F-16, F/A-18, AV-8B, and A-10. The JSF program will also pit P&W against GEAE for the acquisition of the engines powering the aircraft.

The tri-service family would entail a single basic airframe design with three distinct variants: Conventional Take-Off and Landing (CTOL) for the U.S. Air Force (USAF) to complement the F/A-22 *Raptor* and replace the aging F-16 *Fighting Falcon* and the A-10 *Thunderbolt*; Short Take-Off/Vertical Landing (STOVL) for the U.S. Marine Corps (USMC) to replace both the AV-8B *Harrier* and the F/A-18C/D *Hornet*; and a Carrier (CV) variant for the U.S. Navy (USN) to replace the F/A-18A-Ds and to complement the F/A-18 E/F *Super Hornet.*

Figure 11. JSF Logo

Boeing, Lockheed Martin Aerospace Company (LMAC), McDonnell Douglas, and Northrop Grumman were each awarded fifteen-month Concept Definition and Design Research (CDDR) contracts in December 1994. Northrop Grumman and McDonnell Douglas/British Aerospace teamed shortly after the CDDR contracts were awarded. The contractors refined their Preferred Weapons System Concept (PWSC) designs and performed a number of risk reduction activities (e.g., wind tunnel tests, powered-model STOVL tests, and engineering analyses).

In the spring of 1995, all three of the contractor teams selected derivatives of the Pratt & Whitney (P&W) F119 engine to power their aircraft. Accordingly, in November 1995, P&W was awarded a contract for preliminary design of each of the primary JSF engine concepts. The P&W F119 flight test engines performed very well during flight test with no problems noted.

The Secretary of the Air Force selected the Lockheed team and awarded the System Development and Demonstration (SDD) contract.

Foreign partners were sought to help finance the development and test of the program and in exchange, partners receive earlier acquisitions of the aircraft plus other financial and non-financial benefits. The JSF program allows foreign countries to become program partners at one of three participation levels, based

on financial contribution. As shown in Table 1, the foreign partners have contributed over $4.5 billion, or about 14 percent, for the system development and demonstration phase and are expected to purchase about 722 aircraft beginning in the 2012-2015 timeframe. Israel and Singapore have recently begun to participate in the program as security cooperation participants, a non-partner arrangement, which offers limited access to program information, without a program office presence. According to DoD, foreign military sales to these and other non-partner countries could include an additional 1,500 to 3,000 aircraft.

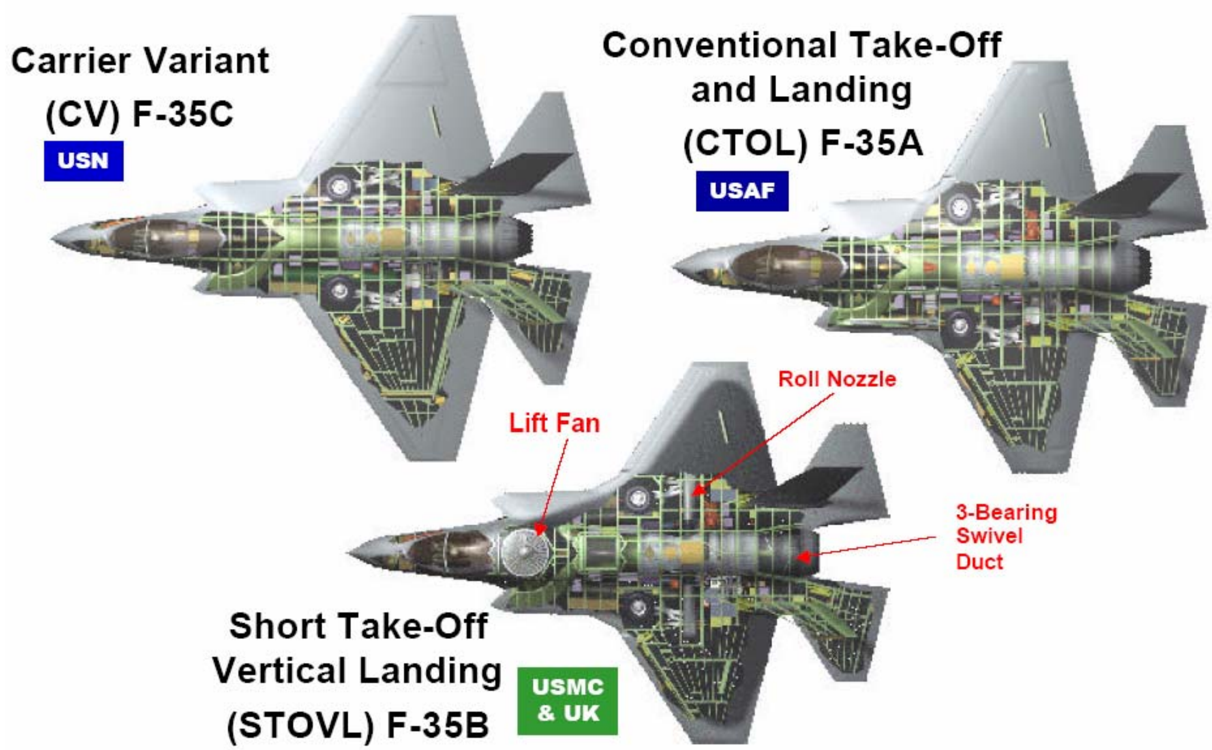

Figure 12. F-35 Variants

In return for their contributions, partner countries have representatives in the program office with access to program data and technology; membership on the management decision-making bodies; aircraft delivery priority over future foreign military sales participants; guaranteed or potential waiver of nonrecurring

aircraft costs; potential levies on future foreign military sales aircraft sold; and improved relationships for their industry with U.S. aerospace companies through JSF subcontracting opportunities.

For example, the United Kingdom – which is committed to contribute just over $2 billion in the system development and demonstration phase – is a Level I full collaborative partner, with benefits such as:

- 10 staff positions within the JSF Program Office, including senior positions on integrated product teams;
- Participation in cost versus performance trade-off and requirement setting processes, resulting in British military needs being included in the JSF operational requirements document; and
- Involvement in final source selection process for the system development and demonstration contract award.

Conversely, the five Level III partners, which are committed to contribute between $125 million and $175 million, each have one program office staff member and no direct vote with regard to requirement decisions (Schinasi, 2003, p. 11).

Table 1: JSF Partner Financial Contributions and Estimated Aircraft Purchases

	System development and demonstration			Production	
Partner country	Partner level	Financial contributions (in millions)[a]	Percentage of total costs	Projected quantities	Percentage of total quantities
United Kingdom	Level I	$2,056	6.2	150	4.7
Italy	Level II	$1,028	3.1	131	4.1
Netherlands	Level II	$800	2.4	85	2.7
Turkey	Level III	$175	0.5	100	3.2
Australia	Level III	$144	0.4	100	3.2
Norway	Level III	$122	0.4	48	1.5
Denmark	Level III	$110	0.3	48	1.5
Canada	Level III	$100	0.3	60	1.9
Total partner		$4,535	13.7[b]	722	22.8
United States		$28,565	86.3	2,443	77.2

Sources: DOD and JSF program documents and AECA project certifications to Congress.

[a]Chart values do not reflect any nonfinancial contributions from partners (see app. II).

[b]Percentages do not add due to rounding.

Table 1. Foreign Partnerships (Schinasi, p. 10)

8. Joint Strike Fighter Propulsion Acquisition

In the summer of 1995, Congress directed the JSF Joint Program Office (JPO) to pursue a second engine source. The purpose was to maintain engine competition during production in the JSF program similar to the 'Great Engine War'. In late November 1995, initial development contracts were awarded to P&W for an F119 derivative (based on the engine for the F/A-22 *Raptor*) and to a GEAE/Allison (later Rolls Royce) team for design studies for the YF120 (based on the latest F110 variants) for the JSF (Younossi et al., 2002, p. 22).

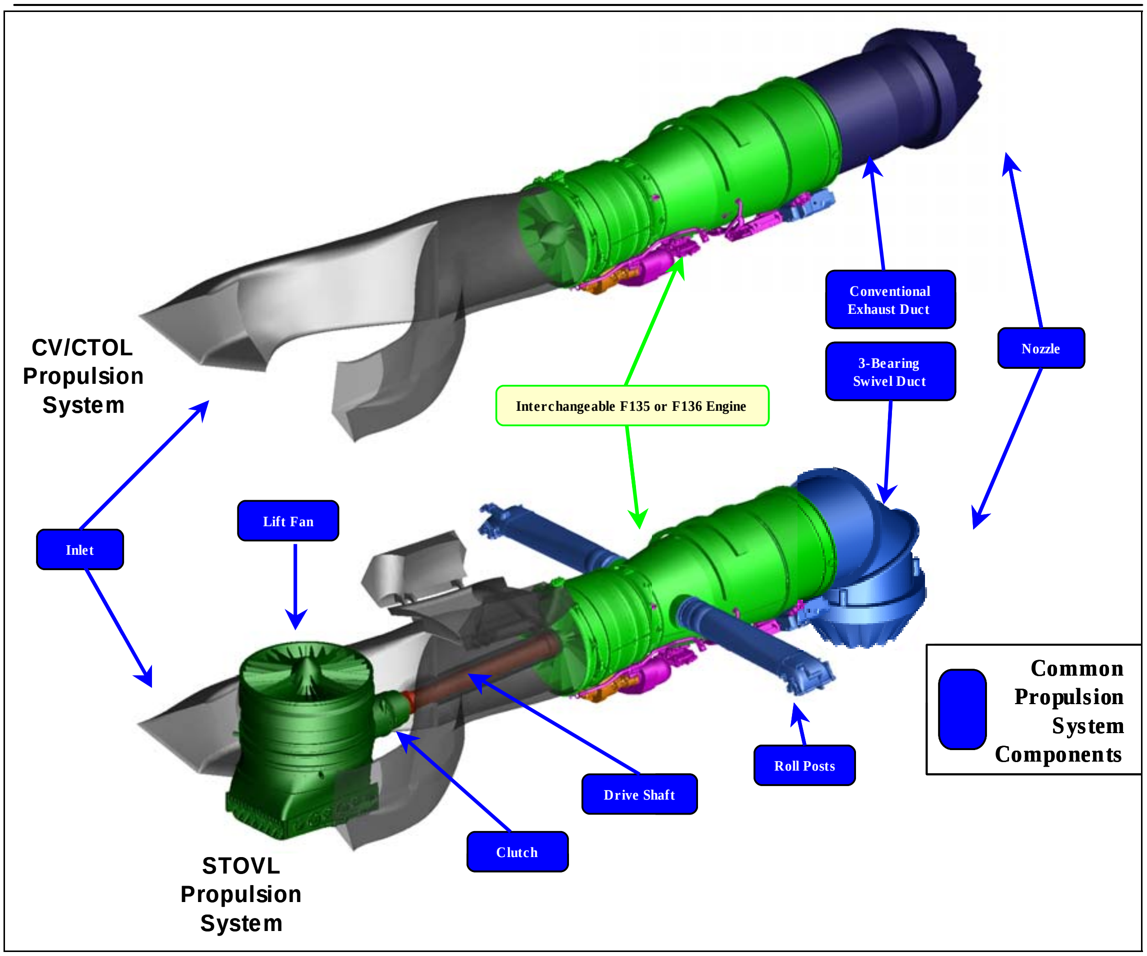

Figure 13. Propulsion Commonality

The two basic engine designs (from front frame through the exhaust frame) would be interchangeable in the aircraft and share common modules (exhaust and lift system) and selected components (see Figure 13.).

The requirement for a common aircraft with a common support system developed and integrated by Lockheed Martin has demanded that the two engine companies cooperate and share design data until the competition formally begins. This unique relationship dubbed ‘coopetition’ (an amalgamation of cooperation and competition) is unprecedented in systems acquisition. The mandate for a common support system alleviates the logistical impact of having *two* engine-specific: training systems, sets of support equipment, technical data systems, and logistic information management systems.

The engines will develop and demonstrate the latest technology in Prognostics and Health Management (PHM) to *predict* impending failures and stimulate the support system to restore the engines *before* secondary damage or lost sorties occurred.

The General Electric Aircraft Engines/Rolls Royce Fighter Engine Team (FET) would produce the F136 (based on the F120 design) lagging the F135 design by approximately five years to be ready for procurement competition beginning in the year 2013. The requirement for a common aircraft with a common support system developed and integrated by Lockheed Martin has demanded that the two engine companies cooperate and share design data until the competition formally begins. This unique relationship dubbed ‘coopetition’ (an amalgamation of cooperation and competition) is unprecedented in systems acquisition.

The JSF propulsion systems will be procured in seven Low Rate Initial Production (LRIP) Lots. The F135 engines will be procured from P&W in LRIP I-V. The F136 engines will be procured on a non-competitive basis from the FET in LRIP IV-V. The exact purchase split between P&W and the FET in lots IV-V has not been determined yet. Competition between P&W and the FET will begin

in Lot VI. Common propulsion system components will be procured on a sole-source basis from P&W during LRIP Lots I-III. The forces of competition, performance-based logistics, and contract incentives will lead to the best value for affordability, supportability, and safety.

9. Pratt & Whitney F135 Engine Description

The Pratt & Whitney F135 advanced propulsion system will utilize cutting edge technology to provide the F-35 with higher performance than conventional fighter aircraft. The engine consists of a 3-stage fan, a 6-stage compressor, an annular combustor, a single stage high-pressure turbine, and a 2 stage low-pressure turbine. P&W also is designing and delivering the Lift Fan (from Rolls Royce) and other lift system components as well as the variable geometry nozzles specific to the STOVL and conventional variants.

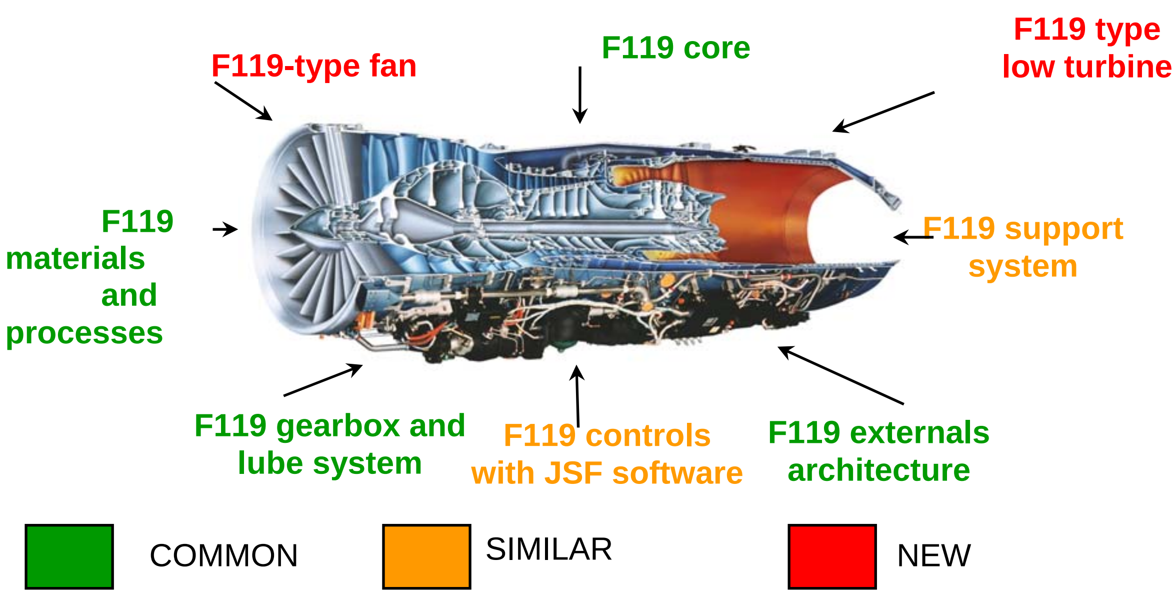

Figure 14. P&W JSF119 engine and relationship to the F-22/F119

The F135 is currently in the System Design and Demonstration (SDD) Phase and is using the technology from the F/A-22 *Raptor* F119 engine core and the JSF119 which powered the JSF concept demonstrator aircraft for fly-off.

During SDD the F135 test engines will undergo a range of ground and flight tests to simulate various mission profiles. In these tests, the engines will be run for hours throughout various flight envelopes to ensure they meet performance requirements. The first CTOL F135 engine test occurred on 11 October 2003. The First STOVL F135 engine test occurred on 14 April 2004. By the end of SDD, the F135 will have accumulated 10,000 operational test hours (JSF Public Affairs, *F135 Description,* 2003).

10. GEAE/RR F136 Engine Description

The GEAE Rolls-Royce Fighter Engine Team (FET) F136 engine lags the F135 development to match F136 engine design as closely as possible to that of the final aircraft configuration, thereby minimizing changes and keeping pace with evolving aircraft demands prior to entering SDD.

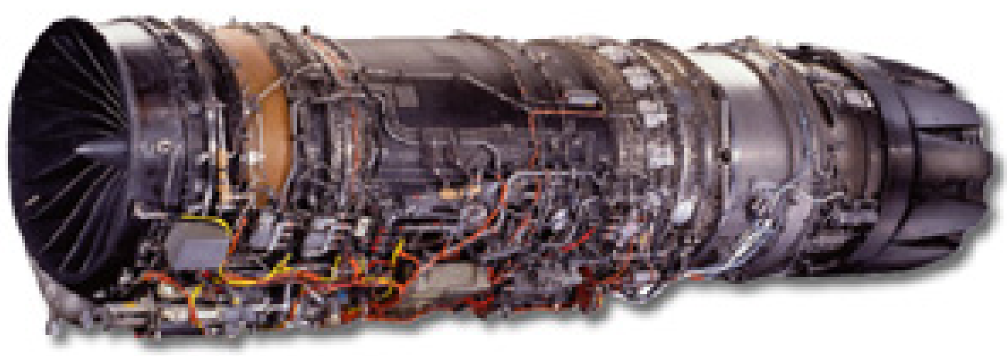

Figure 15. F136 Engine

The F136 engine consists of a 3-stage fan, 5-stage compressor, a 3-stage low-pressure turbine section, single stage high-pressure turbine, and a radial augmentor based on the F110 and F120 Programs. The Pre-SDD F120 engine was a growth engine from the F110.

The F136 team will transition into the SDD phase of their program later in 2005. The first F136 CTOL engine was successfully tested for the first time on 22 July 2004. Testing on the first F136 STOVL propulsion system began on 10 February 2005. (JSF Public Affairs, *F135 Description,* 2003).

11. Rolls-Royce Lift System

While Rolls-Royce is a member of the Fighter Engine Team with GEAE on the F136, they are also subcontracted to Pratt & Whitney on the F135 to provide the Lift System for the F-35. The Lift System is comprised of the Lift Fan, Clutch, Drive Shaft, Roll Posts and the Three Bearing Swivel Module (3BSM).

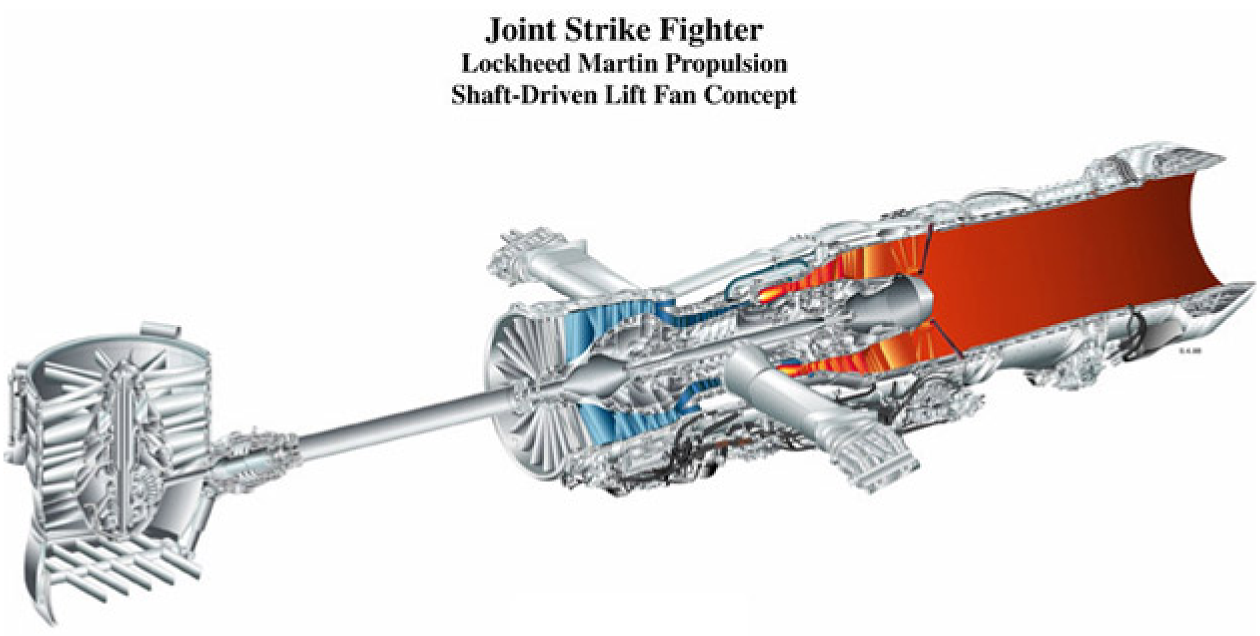

Figure 16. STOVL Lift Fan

Lockheed Martin developed the idea for a Short Take-Off Vertical Landing (STOVL) lift system that uses a vertically oriented Shaft Driven Lift Fan (SDLF). A two-stage low-pressure turbine on the engine provides the horsepower necessary to power the Rolls-Royce-designed Lift Fan. The Lift Fan generates a column of cool air that provides nearly 20,000 pounds of lifting power using

variable inlet guide vanes to modulate the airflow, along with an equivalent amount of thrust from the downward vectored rear exhaust to lift the aircraft. The Lift Fan utilizes a clutch that engages the shaft drive system for STOVL operations. The SDLF concept was successfully demonstrated through a Large Scale Powered Model (LSPM) in 1995-96 and during the flight-testing of the X-35B during the summer of 2001. The Lift Fan™, a patented Lockheed Martin concept, is being produced by Rolls-Royce Corp. in Indianapolis, Indiana and in Bristol, England (JSF Public Affairs, *F135 Description,* 2003).

D. SUMMARY

This chapter explored the similarities and differences in the F-16 and JSF acquisitions and the overall approach of the study.

The first Great Engine War began with early F-15 and later F-16 operational testing. The aggressive requirements and emphasis on high performance placed a high demand on Pratt & Whitney to deliver a great leap forward in propulsion technology. The engine met or exceeded the performance requirements but unforeseen shortfalls caused compressor stalls and reduced engine durability. The disagreement between the USAF and P&W over who would pay for the design fixes led to a rift in the relationship. Rather than accept the ‘take it or leave it” approach from P&W, the USAF sought another source for engines. The resultant competition produced another engine suitable for the USAF and did induce P&W to fix their design and become more responsive to the USAF’s needs. The Joint Strike Fighter will also compete the procurement of engines to ensure each contractor is incentivized to produce the best design at the least total life cycle cost to the Government.

THIS PAGE INTENTIONALLY LEFT BLANK

II. LITERATURE REVIEW

A. INTRODUCTION

The Great Engine War has been the subject of quite a few Masters Thesis topics and other directed studies. The vast majority of the studies agree that the competition was successful. Not surprisingly, each of the studies had a different perspective. Some focused only on the cost/benefit, while others used a broader view to include the intangible aspects such as customer satisfaction and perceived industry attitudes.

The Joint Strike Fighter program literature included below is topical in nature and purposely limited to the unclassified/public-releasable information to keep this paper unclassified.

B. F-16 PROPULSION ACQUISITION

Many studies were done shortly after the first few years of the F-16 engine competition and are dated circa 1988. My research centered on six representative studies. Even though each one had a slightly different focus, they all agreed that the competition was the 'right thing to do' and that the outcome for the Government was positive as each company strived to improve their products. However, the cost studies are less definitive and cost may not be the lead factor in a future decision to compete the engines (see Table 2: Summary of Studies).

General themes that emerged from each study were:

- The competition was a great success
- Cost savings were not a factor in the success
- Competition improved manufacturer responsiveness
- Competition should be pursued in future acquisition programs

Studies which support these general themes are discussed, below.

Summary Of Studies									
	Successful Competition?		Cost Savings?			Responsiveness?		Future Applications?	
Reports	Yes	No	Large	Small	Inconclusive	Improved	Unimproved	Yes	No
Metamorphosis of Business Strategies and Air Force Acquisition Policies in the Aerospace Propulsion Industry: Case Study of the "Great Engine War" (Jon Steven Ogg)	√				√	√			√
The Air Force and the Great Engine War (Robert W. Drewes Col, USAF)	√			√		√		√	
Analysis of the Air Force and the Great Engine War (Victoria Mayes)	√				√	√		√	
Alternate Fighter Engines Competition Study (Jeffrey A. Hoover)	√			√		√		√	
The development of the F100-PW-220 and F110-GE-100 Engines: A Case Study of the Risk Assessment and Risk Management (Frank Camm)	√				√	√		√	
Fighter Engine Competition: A Study of Factors Affecting Unit Price (Brian R. Leginus)	√				√	√		√	

Table 2. Summary of Studies

1. Metamorphosis of Business Strategies and Air Force Acquisition Policies in the Aerospace Propulsion Industry: Case Study of the "Great Engine War" (Ogg, 1987)

Perhaps the definitive summary of the 'war', it explored the history and the motives that guided the government and each of the engine companies. It summarized the competition as a success, but qualified the declaration with a caveat that many factors came together and it should not be used as a blanket endorsement for competition in all future situations. An interesting question posited is whether the funding used for development of the alternate engine could have been better utilized in fixing F100 design issues.

Some conclusions and recommendations were:

- Begin competition sooner. By the time GEAE was brought in, P&W had already produced over 3,000 F100 engines for the F-15 and F-16 programs.
- Engine competition is inherently unique. The market cannot be easily entered and exited. Producers must be rigorously

evaluated for suitability and performance which leads to a very long lead time. There is an enormous tooling and manufacturing production capability investment required. Lastly, the aspect of national security cannot be ignored.

- Politics plays a very influential role in the success and outcome of a competition.
- In a competitive source process, the detailed cost data and certification process is unneeded. This should streamline acquisition and allow for refinement of bids at the beginning of each competitive selection.

2. The Air Force and the Great Engine War (Drewes, 1987)

A great over-all study of the competition, its conclusions were pro-competition, with the following specific recommendations:

- Competition forced Pratt to become much more incentivized to fund and implement changes to their design to improve reliability and performance.
- Competition should be extended as far as feasible in the acquisition process, preferably until the last engine is bought. There is the recognition that competition may not make sense late in the program when only a few spare engines are being procured in small quantities where two manufacturers can't sustain a production line.
- Competition for engines requires a high volume to support a large fleet. Competing the relatively small fleet of the B-2 *Spirit* F117 engine engines would likely be cost-prohibitive.
- Stated the argument for using Total Accumulated Cycles (TACs) versus the standard 'engine operating hours' currently used

to measure the life consumed of a military engine. It recognizes the increased rotor wear from throttle transients due to acceleration and deceleration stresses.

3. Analysis of the Air Force and the Great Engine War (Mayes, 1988)

This Master's Thesis was written for the Air Force Institute of Technology in pursuit of a degree in Logistics Management. It was intended as a follow-up to the aforementioned book by Col Drewes. It reinforced the positive outcome of the competition. It focused on some of the logistical impacts to the customer.

- Included a discussion comparing the USAF Great Engine War with the USN failed competition for engines in the F/A-18 *Hornet.* The USN competition failed because the competition was for a second vendor to build-to-print the original engine. This failed as the original vendor (GEAE in this case) was not incentivized to provide complete assembly instruction to its competitor.

- Highlighted the Pratt strategy for winner-take-all in the initial competition was unreasonable and showed the need for having a minimum sustainable buy from each vendor and competing the remainder of the buy.

- Reinforced the positive attitude adjustment on the part of Pratt after losing the majority of the first few buys to GEAE.

- Recommended that competition should be declared from the outset so each manufacturer can right-size their production capacity.

- Recognized that Foreign Military Sales (FMS) tends to follow USAF acquisition lead. Winning the majority of the USAF competition helped win the lion share of the FMS market also.

- The military engine market is different from a true ‘open’ market system in which manufacturers can freely enter or leave the market place. The quasi-monopoly does not lend itself to truly lower prices, only an artificially supported industrial base.
- Recommended tailoring the contract Statements of Work for each vendor to recognize the differences in the offerers.
- Addressed the logistic impact of two engines on support equipment, sparing, and mixing two different engines in a squadron or Wing.

4. Alternate Fighter Engines Competition Study (Hoover, 1986)

Written from a contracts and cost analysis perspective, it is a good scrub of the financial aspects of the competition.

- The process for submitting engine acquisition budget estimates in advance of the pricing offers from the manufacturers introduced unavoidable complexity. No recommendation to alleviate this situation was offered.
- Competition was beneficial from a cost aspect, but it is admittedly difficult to capture all the costs associated with the acquisition of two competing engines.

5. The Development of the F100-PW-220 and F110-GE-100 Engines: A Case Study of the Risk Assessment and Risk Management (Camm, 1993)

This study looked at the dynamics of the competition from a program management stand point. As the title states, the focus is the risk of new engine development and its transfer to the manufacturers under the competition. Simply stated, the government won’t procure the engine that fails to meet the specification, so the contractor must assume the development cost risk.

- Continuity in System Program Office personnel and structure contributes to the success of engine competition and acquisition in general.

- Discussed the impact of the high congressional and USAF management interest in the engine acquisition. The special interest probably positively affected the scrutiny the contractors put in to their proposals.

- Recognized the hurdle of funding and managing two engine programs to develop a competitive environment. The next USAF fighter (to later become the F/A-22 *Raptor)* did not compete the engines but remained sole-source.

- Contract type (fixed-fee versus cost-plus) affects risk transfer in engine development. A fixed fee contract puts the risk of failure (higher engineering costs to develop a suitable system) on the contractor. Cost-plus is the preferred contract type for new development programs where risk is inherently higher. This puts the risk of higher engineering costs on the Government.

6. Fighter Engine Competition: A Study of Factors Affecting Unit Price (Leginus, 1998)

This was another cost study to determine the value of the competition. It is much more clearly focused on the price paid per engine rather than the total costs (see the Hoover study, above). Competition caused each manufacturer to begin at or near the 'bottom' of the learning curve (Nahmias, 2001):

> As experience is gained with the production of a particular product, either by a single worker or by an industry as a whole, the production process becomes more efficient.
>
> By quantifying the relationship that describes the gain in efficiency as the cumulative number of units produced increases, management can accurately predict the eventual capacity of existing facilities and the unit costs of production.

Studies of the aircraft industry undertaken during the 1920s showed that the direct-labor hours required to produce a unit of output declined as the cumulative number of units produced increased. The term learning curve was adopted to explain this phenomenon.

This is manifested by the subsequent engines produced could not be produced significantly cheaper by more experienced technicians. However, ignored here is the fact the first engines produced are used for test and only the *production* engines are competed. The key is defining exactly which engines (first *test* articles or first *production* units) are considered the 'first units produced' and which determines where the costs are on the curve. See Table 3. Learning Curve Example (below). The test engines are the first engines assembled and have the highest cost to produce whereas the first production engines will cost less to produce as processes are refined and experience is gained. Engines typically follow a 70-75 % experience curve.

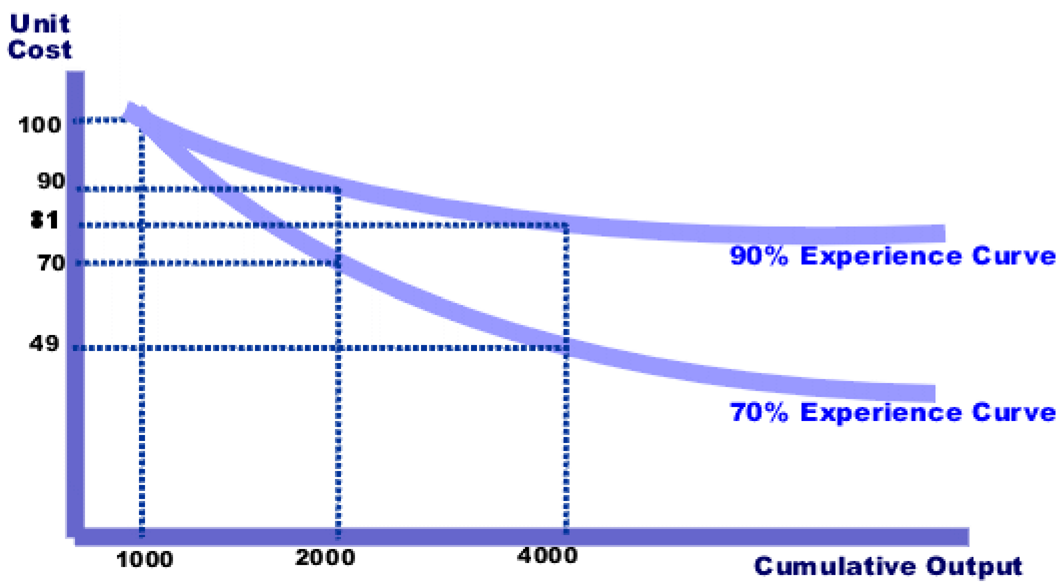

Table 3. Learning Curve Example (Wikipedia, 2005)

By analyzing the learning curve, normalizing quantities and factoring inflation the author arrives at an index for the *should* cost for the engines before and after competition.

- Of importance was the discovery that neither engine quantity, inflation, nor competition *directly* affects engine unit cost. The unit prices of the engines did lower after the competition began. It is just not clearly understood *why*.
- Competition caused each manufacturer to begin at or near the 'bottom' of the learning curve.

However, ignored here is the fact the first engines produced are used for test and only the *production* engines are competed.

C. JOINT STRIKE FIGHTER PROPULSION ACQUISITION

Pratt and Whitney Military Engines, East Hartford, Conn., has been awarded a contract for more than $4 billion to develop the F135 propulsion system. This contract will cover ground and flight testing and production qualification of the Pratt & Whitney propulsion system.

The Joint Strike Fighter acquisition strategy also calls for the development of two propulsion systems. The Pratt & Whitney system will compete, in production, with one developed by the team of General Electric and Rolls Royce. GE/RR are expected to receive a contract for the next phase of development of that system in the next few weeks. The P&W and GE/RR engines will be physically and functionally interchangeable in both the aircraft and support systems. All JSF aircraft variants will be able to use either engine. The competition starts in fiscal 2011 and continues through the life of the program to reduce risks. (JSF Public Affairs, *F135 Description,* 2005)

The Joint Strike Fighter propulsion acquisition strategy is significantly different from the F-16 engine acquisition. Although there are many similarities between JSF and the F-16 (they are both lightweight fighters with high affordability achieved through high foreign and domestic sales volume), the *key differences* and their *potential impacts* are discussed, below:

- The JSF engine competition has been congressionally mandated and planned for from the outset. *This has allowed P&W and the Fighter Engine Team (FET) to plan accordingly for production capacity. It has also help guide decisions by knowing the maximum percent of the total fleet one manufacturer could provide. It has affected contractor responsiveness from the outset for maximum value to the government.*

- Each propulsion system must be interchangeable in the aircraft (the F-16 engines were not interchangeable). *This has an immediate affect on engine design, preventing a 'performance race' at the expense of reliability. It also enables the customer to mix engines at the squadron level if desired.*

- The JSF early development has declared 'Coopetition' (the cooperation of the two companies in design integration and then, later, the competition as production begins). *This allows some reduction in the development cost of the FET F136 as it finalizes its design after the aircraft design has stabilized.*

- One Autonomic Support System will meet the customer's needs for maintenance, supply, training, etc. for both engines. All the Lockheed-developed flightline support equipment is designed to support both engines. *This reduces the logistic impact of having two engines for the same aircraft. This also enables the customers to easily transition from one engine variant to another.*

- Shared Prognostics and Health Management (PHM) sensors where feasible. New to the JSF is the ability to predict engine component failure and react accordingly. This will reduce secondary damage and improve aircraft availability as maintenance becomes a planned activity instead of a nasty surprise. *By sharing common PHM sensors and components where feasible, the development cost and risk for the engines will be reduced.*

D. CHAPTER SUMMARY

The Great Engine War was a success, but mostly for its intangible benefits such as improved customer response and contractor investment in reliability improvements. No definitive proof of a substantial cost savings is evidenced.

The planning for the JSF engine competition already reflects many of the lessons learned from the F-16 acquisition. New strategies show much promise to reduce JSF propulsion acquisition costs and keep the contractor responsiveness at a high level.

The next section will describe the process and sound methodology to guide the research.

III. RESEARCH METHODOLGY

A. INTRODUCTION

The research consisted of personal interviews conducted in person or by telephone and recorded for accuracy. The interviews were carefully crafted and seven key stakeholders were selected to represent the small cadre of decision makers in the Government and industry.

1. Interviewee Selection

The Interviewee selection process began once the research on the F-16 program was complete. The research revealed those positions which were pivotal in shaping the outcome[5]. The JSF Joint Program Office, P&W, GEAE, and the USAF Propulsion Support Program Office were then contacted for potential interviewees.

The selected interviewees were:

- **Otha Davenport** (Propulsion SPO Lead)
- **Ken Kohrs (**Propulsion SPO Warranty Management)
- **Ed O'Donnell** (P&W F100 International Programs)
- **Ken Murphy** (GEAE F110 Foreign Military Sales)
- **Ken Poblenz** (GEAE F110 Program Manager)
- **Pat Mattix** (GEAE F110 Warranty Administration)
- **Phil Hughes** (GEAE F110 Customer Support)
- **Stoney MacAdams** (JSF Propulsion Acquisition IPT Lead)

[5] Interestingly, General Dynamics (GD), which later became Lockheed Martin Aeronautics Company (LMAC), was never mentioned in any of the studies as a factor in the Government decision to compete the engines.

2. Developing the Questions

The questions for the interview were carefully crafted to elicit common themes and to highlight the different viewpoints representing the experiential perspective of each interviewee.

a) Composing Appropriate Questions

To ensure responses would not be negatively colored by the choice of questions, a careful analysis of each question was performed. It was important to select questions which didn't ask for specific data, but relied on the experiential perceptions of the interviewee. From the GAO guidance:

> Avoid questions that require the interviewee to perform "audit work" to answer—that is, to consult records or other information sources.
>
> Personal questions should be avoided or used with extreme care. The same is true of questions that would tend to incriminate or show the interviewee in a bad light, particularly since the interview might terminate if they were asked (Chelimsky, 1991 p. 23).

Because many of the interviewees made decisions that were enormously important to their respective organizations, I was careful to ensure the questions were neutral in tone and devoid of any possible bias.

b) Organizing the Questions

Additional GAO guidance is:

> Highly effective interviews center on answering only or possible two primary questions. Secondary questions help gain a deeper understanding of the subject's knowledge and often yield valuable learning. If there are too many primary questions the subject is never fully explored and the interview results are usually less than adequate.
>
> To be highly effective, the interview must have secondary questions which are unambiguous and support the primary question. Each

> question should be 'open-ended' to avoid single word responses. (Chelimsky, 1991 p. 23).

The research interviews conducted were centered on answering the primary question: 'What lessons learned can be derived from the "Great Engine War" to create recommendations for managing the Joint Strike Fighter engine competition?' To further narrow the scope of the interview, but not limit it, the following secondary questions were used:

- What were the positive and negative affects of the "Great Engine War" on F-16 acquisition decisions, production and support costs, engine performance, engine supportability, etc., and how might these factors apply to the JSF engine acquisition processes?
- What were the F-16 competition criteria, how well did the contractors meet those criteria, and how might those criteria need to be changed for the JSF engine competition?
- How did Foreign Military Sales (FMS) factor into the F-16 engine competition, and how should it be managed for the JSF?

c) Conducting the interviews

To gain the most from each interview, discussions began with introductions and the purpose of the interview. Once at ease, each question was asked. Interview answers were recorded to facilitate an accurate account. GAO guidance on conducting interviews was followed:

> To oversimplify, the role of the interviewer is to ask the questions, while that of the interviewee is to respond with answers. Actually, the interviewer must perform at least eight major tasks:

- develop rapport with the interviewee and show interest,
- give the interviewee a reason to participate,
- elicit responsiveness from the interviewee,
- ask questions in a prescribed order and manner,
- ensure understanding,
- ensure non-bias, and
- obtain sufficient answers (Chelimsky, p. 78)

Each interviewee was encouraged to fully answer each question and affirmed the answers in a non-committal way. Careful attention was given by the interviewer to not judge the individual or respond with any pre-conceived ideas on the topic. As a result, the interviewer was rewarded with a rich diversity of responses. A genuine representation of the facts, opinions, and emotions of each interviewee emerged.

B. CHAPTER SUMMARY

Research questions had to be crafted carefully to support qualitative analysis methods, but open enough to capture any new knowledge and fully delve into the subject. The interviewees had to be the actual veterans of the war willing to give their experience first-hand. It was very important to ask each question and then *listen* to the responses to craft a pertinent follow-up question if necessary and to record all answers. The following section fully examines the data collected and provides the reasoning for conclusions.

IV. DATA ANALYSIS

A. INTRODUCTION

From the interviews and research, a clearer picture of the tumultuous time of the great engine war emerged. Each stakeholder represented another facet of the situation clearly colored by their position and perception.

B. ORGANIZATIONAL BEHAVIOR PROCESS

To guide the interviews, an understanding of the influences that drive each of the stakeholders was needed to better frame their responses and weight them correctly in the final analysis.

Each organization can be viewed as a system of actors which have influences and in turn exert influence on other members. To better understand the perspective of each stakeholder, it is useful to perceive the organization through the filters of the ‘Strategic Design’, ‘Political’, or ‘Cultural’ lens of organizational behavior (Ancona, Kochan, Scully, Van Maanen, & Westney, 1999, Module 2, p.7):

1. Strategic Design Lens

Certainly considered the ‘traditional’ view, the strategic view focuses on the organizational alignment of each team member. The roles are clearly defined and each member can *see* the reporting relationships based solely on function. Although very practical for an internal process such as a factory, it is inadequate for perceiving the motivations which also drive the decisions in an organization.

2. Political Lens

The political lens looks at how power and influence are distributed and wielded. Very often the *real power* in an organization does not conform neatly to the organization chart created by management to achieve the organization's stated goals. The political lens lets us see the motives and sometimes hidden agendas that guide actions of each stakeholder.

3. Cultural Lens

The cultural lens is very useful in identifying the underlying causes for why certain organizations seem to operate so much more cohesively than other similar organizations as viewed through the strategic design or political lens. It attempts to bring to light the 'whys' an organization reacts as it does to each challenge. It focuses on the personal history, norms, and basic human emotions and desires that build strong teams.

The research used a combination of each of the lens – to properly view the forces and influences on each stakeholder. This approach yielded valuable insight to possible motives in the responses.

The stakeholders in the F-16 Great Engine War are depicted in Figure 17 (below).

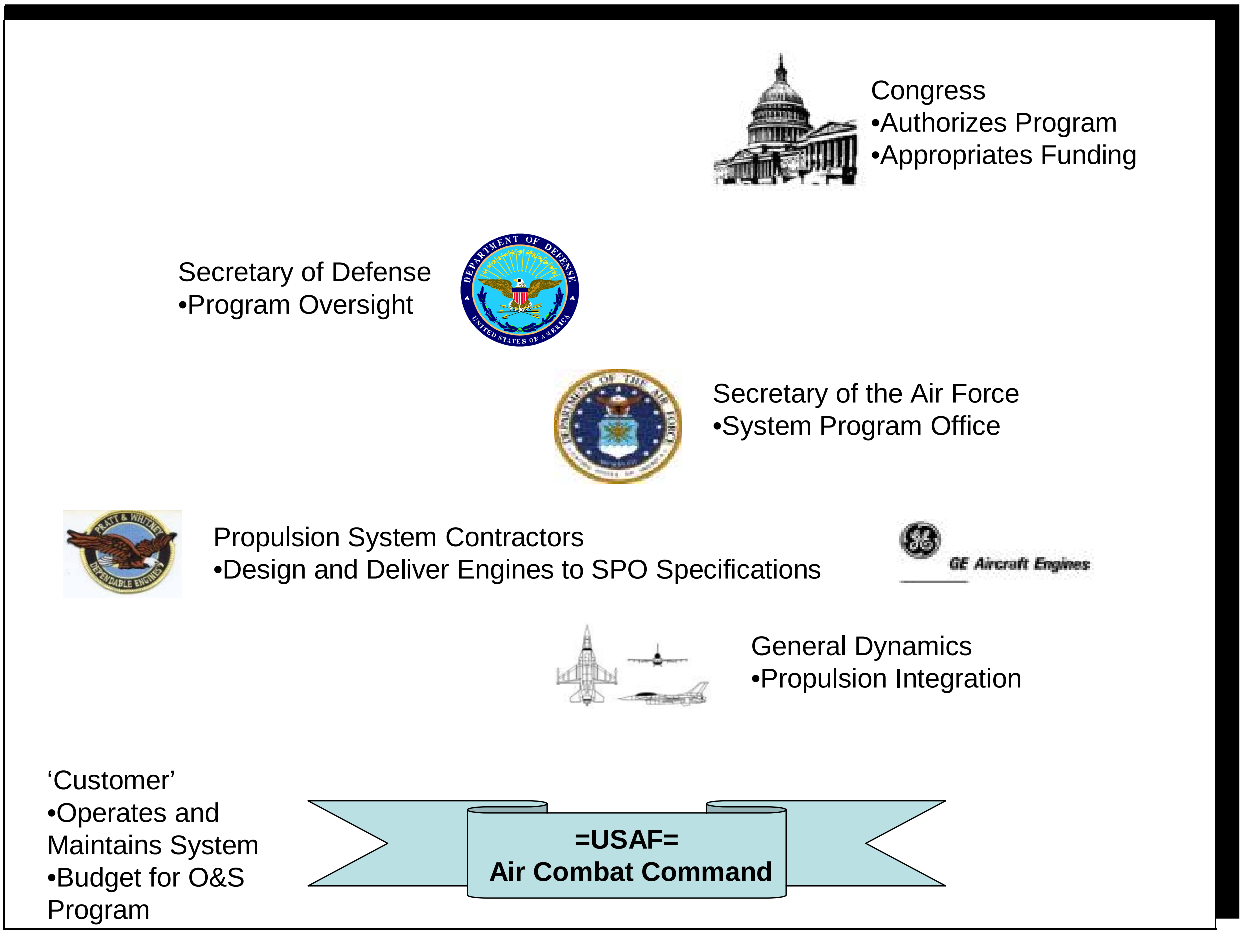

Figure 17. F-16 Engine Competition Stakeholders

Each of the stakeholder organizations is briefly described, below:

- **Congress** The United States Congress authorizes programs to proceed and appropriates funding to pay for them. Each member is elected and is very cognizant of each constituent's interests on every bill before them. Each program strives to answer queries and support investigations to keep 'The Hill' happy.

- **Office of The Secretary Of Defense (OSD)** OSD provides an integrating and oversight function for military programs. All

though OSD doesn't have the budget authority over the services, it does act as a gatekeeper to ensure the highest levels of scrutiny and review.

- **Secretary of the Air Force (SAF)** The SAF staff allocates funding and has direct oversight of each USAF program. The SAF is concerned with maintaining the appearance of proprietary and impartial acquisition management while meeting the needs of the warfighters. The SAF delegates authority to a System Program Office (SPO) to manage and balance the requirements and contract for systems which will meet the performance demands. The SPO is usually focused on the immediate performance of the program and is keenly aware of the customer's evolving desires. The SPO Program Manger and much of the staff are subject to limited terms of involvement as the USAF reassigns its officers with regularity. Program continuity is found in the SPO civilian support staff.

- **Contractors** For the F-16, General Dynamics (GD) was selected as the prime contractor to design, develop, and deliver the entire weapon system using SPO-procured engines as 'Government Furnished Equipment' (GFE)[6]. Pratt & Whitney was selected to integrate the F-15's F100 engine to power the aircraft as GFE. GEAE designed and delivered the F110 under the Alternate Engine Program. Each contractor is incentivized to meet the SPO's requirements and to please company shareholder's concerns for short-term profitability.

- **Tactical Air Command (TAC)** The ultimate customer for the F-16, the TAC (now Air Combat Command) fighter squadrons budget for operations and maintenance funding from Congress

[6] The other option was for the government to let General Dynamics select and contract for the engine and deliver it as 'Contractor Furnished Equipment' (CFE) with the aircraft.

to fly and maintain the weapon system in combat. The TAC desire is for safe, effective and affordable weapon systems.

In this case, the Great Engine War was an emotional time for the stakeholders. An analysis of the interviews as seen through the cultural lens yields valuable insight:

- The P&W employees would feel betrayed by a faithful customer (USAF) that would call into question Pratt's commitment and service and try to take their business away. The company's management worked to circumvent the SPO, SAF, and OSD by pushing Congress to act favorably for them and quell the competition initiative.
- The GEAE team had lost the lion share of the fighter engine business to P&W would be grateful to get a chance at the potentially lucrative program and be eager to please. The focus was on gaining a share of the market and working to meet the SPO's requirements. After all, 'part of something is better than all of nothing'!
- The F-16 System Program Office discovered it no longer had the direct power to influence P&W to meet USAF customer demands for as-delivered performance of the engines. The threat of competition now empowered the SPO to influence the outcome. The initiators of the competition would be expected to act with human nature, that is to say, pre-disposed to justify their decision to compete and not be critical of it. There was resentment towards P&W for going straight to Congress to attempt to sidetrack the competition effort. (Camm, 1993)
- General Dynamics was able to keep out of the fray and emerged unscathed throughout the 'war'. The neutral posture of GD

management certainly helped in keeping them from suffering any consequences.

The political dynamic is evidenced in the Government Accounting Office audit requested by none other than the Senators from Connecticut and Florida (home of P&W's two main plants). The GAO audit and P&W direct appeals to Congress were ineffective. The effort to exert external influence on the SPO only served to increase the Government resolve for competition to bring back into balance the power in the relationship.

C. RESEARCH ANAYLSIS METHOD

The research analysis relied on *qualitative* versus *quantitative* methods. The quantitative approach is based on 'fact tables' of pure data. The researcher then looks for conclusions to understand factors in a situation from the sheer volume of data collected.

Qualitative research on the other hand, is embraced by the social scientific community and relies on relatively few but intensive interviews. The researcher then derives the impacts and focuses on the interviewee's experiences normalized for the cultural factors present. This method recognizes that every person perceives a situation colored by their experience base, emotions, and personal impacts from a situation (Nagy Hesse-Biber & Levy, 2004).

Interview questions were purposely structured as open-ended and the interview process left room for additional insight and wisdom from the interviewee. Other ways to gain qualitative analysis include:

- Observation (Direct and Indirect)
- Interaction
- Interview
- Narrative (Nagy Hesse-Biber & Levy, 2004)

This research relied on interviews due to the fact that the observed events have already occurred, the stakeholders have all moved on to different jobs or retired, and the inherent efficiency of the interview process.

D. INTERVIEW RESULTS

Research interviews were conducted during the period of 16 April through June 28, 2004. These interviews yielded new knowledge and an affirmation of data provided by previous studies performed on this subject. The general themes that emerged from the actual interview quotes are provided below as they relate to each research question:

1. "What Were The *Positive* Affects Of The 'Great Engine War' On F-16 Acquisition Decisions, Production And Support Costs, Engine Performance, Engine Supportability, Etc., And How Might These Factors Apply To The JSF Engine Acquisition Processes?"

- "Pratt and Whitney proposals following the competition were much more comprehensive and addressed the admitted shortfalls in their design. Pratt responsiveness improved in many large and small ways (S. MacAdams, personal communication, June 28, 2004)."
- "Engine per-unit costs were lower after GEAE entered the market. But the reduction was less than 5%, not a significant difference but more than without the competition. This was due to the engines being closer to the bottom of their learning curve (E. O'Donnell, personal communication, May 12, 2004)."
- "Drove improvements in [engine] design (O. Davenport, personal communication, April 16, 2004)."

- “It forced everyone to ‘sharpen their pencils’ and really look at design and cost. This yields the lowest possible acquisition cost [for the Government]. Foreign Military Sales customers benefited also from improved service (K. Murphy, personal communication, April 23, 2004).”

2. “What Were The Negative Affects Of The ‘Great Engine War’ On F-16 Acquisition Decisions, Production And Support Costs, Engine Performance, Engine Supportability, Etc., And How Might These Factors Apply To The JSF Engine Acquisition Processes?”

- “Supportability was impacted, as support systems were duplicated which increased footprint. This was caused by not having a common aircraft which led to difficulty in determining who would receive F110 or F100 engines/aircraft (O. Davenport, personal communication, April 16, 2004).”
- “Politics affected the Government buy decisions. The perception was that industrial base support was more important than selecting the contractor with the best price (K. Murphy, personal communication, April 23, 2004).”
- “The focus on acquisition cost pushed support costs up. What was needed was a firm metric for total ownership cost (K. Poblenz, personal communication, April 23, 2004).”
- “The advantage was given to better the engine with better thrust performance. This could drive one competitor out of the business if [higher] thrust was a

criteria (E. O'Donnell, personal communication, May 12, 2004)."

- "Aircraft were not interchangeable – affected long lead time and delivery (O. Davenport, personal communication, April 16, 2004)."

3. "What Were The F-16 Competition Criteria, How Well Did The Contractors Meet Those Criteria, And How Might Those Criteria Need To Be Changed For The JSF Engine Competition?"

- "Price to an extent, but quality was greater (E. O'Donnell, personal communication, May 12, 2004)."
- "Warranty and logistic support – of these - warranty was wasted money (K. Murphy, personal communication, April 23, 2004)."
- "Price (acquisition), basing (having to buy in lots to support a complete squadron stand-up. It would be prohibitive to 'mix' squadrons of P&W and GEAE engines), and Operations & Support (O&S) cost (O. Davenport, personal communication, April 16, 2004)."
- "The focus was on improving reliability, warranty, an1d reduction in unit price. The JSF should have a similar focus, but with Performance Based Logistics for sustainment and no warranty. Competition can be expected to change as the program reaches the end of production (when buying only a few spares [engines] a year) (S. MacAdams, personal communication, June 28, 2004)."

4. "How Did Foreign Military Sales (FMS) Factor Into The F-16 Engine Competition and How Should It Be Managed For The JSF?"

- "Kept competition going much longer (K. Poblenz, personal communication, April 23, 2004)."
- "Competition encourages cost/overhead 'offsets'.[7] This is not the most efficient way to allocate costs. Direct sales to FMS customers are 'bad' for competition and can only drive up the Government cost (E. O'Donnell, personal communication, May 12, 2004)."
- "Affects US cost with the potential for different price structures (S. MacAdams, personal communication, June 28, 2004)."
- "Thrust not a factor – but did affect the [FMS] buys! The F110 had more thrust, but more safety issues (O. Davenport, personal communication, April 16, 2004)."
- "Competition is best managed as a 'buying club' for *all* [JSF] customers. The best gains are realized by combined buying power and then dealing with the allocation distribution (S. MacAdams, personal communication, June 28, 2004)."

[7] 'Offsets' are defined as the shift of overhead costs to other non-competed programs. This helps the competed contract price *appear* lower, thus making the competed offer more attractive. Other (non-competed) programs would increase in price.

5. "Should the JSF Pursue a Component Improvement Program (CIP)?"

The CIP is used by in-service propulsion programs to continue development and testing of engines to refine the design for reliability. Each program then requests funding to implement the design improvements as an Engineering Change Proposal. To maintain a fair competition, it is assumed that each JSF propulsion contractor would receive equal amounts of CIP funding.

This was a highly divisive question, with strong sentiments both for and against CIP. As you see from the responses - no interviewee was at a loss for an opinion!

- "Yes! To guide contractors to fix what is important to the government customer - reliability (O. Davenport, personal communication, April 16, 2004)."
- "No! In competition the contractor pays for any [reliability] fixes – why should we pay twice? It doesn't make sense (S. MacAdams, personal communication, June 28, 2004)."
- "Yes! CIP levels the competition or prolongs it (one side never too far from winning next competition round). It could be used to fund thrust or reliability depending on the situation (O. Davenport, personal communication, April 16, 2004)."
- "No! CIP is only needed for sole source acquisition – not for competition (K. Murphy, personal communication, April 23, 2004)."

- “Yes! Contractor profit drives decisions for reliability and not necessarily safety (O. Davenport, personal communication, April 16, 2004).”
- “No! Mission and engine useage is a bigger factor that affects reliability more than design (P. Mattix, personal communication, April 23, 2004).”
- “No! The government used CIP [for the F-16 engines] to ‘level the playing field’ by helping the poor performing engines instead of letting the market force them (O. Davenport, personal communication, April 16, 2004).”

The differences in the responses reflect different viewpoints – sometimes from the same interviewee! Further analysis was performed by properly weighting each argument (both for and against) by the following criteria:

- Applicability to the unique JSF acquisition strategy and environment.
- Compliance with current DoD policy guidance for Performance Based Logistics (PBL).

There are implicit incentives for the contractor to improve product reliability and performance. The two greatest forces are competition and Performance Based Logistics (PBL). Lesser inducements for better product performance are corporate reputation and the expectation of future business. To better understand the force of PBL, refer to the DoD PBL guidance (Defense Acquisition University, 2005):

> Performance Based Logistics (PBL) is the preferred Department of Defense (DoD) product support strategy to improve weapons system readiness by procuring performance, which capitalizes on integrated logistics chains and public/private partnerships. The cornerstone of PBL is the purchase of weapons system

sustainment as an affordable, integrated package based on output measures such as weapons system availability, rather than input measures, such as parts and technical services. The Quadrennial Defense Review (QDR) and the Defense Planning Guidance (DPG) directed the application of PBL to new and legacy weapons systems. PBL Implementation is also mandated by DoD Directive 5000.1, The Defense Acquisition System, May 12, 2003.

The experiences of the interviewees, in most cases preceded the latest DoD guidance and implementation of Performance Based Logistics (PBL). As a result, these responses must be factored against current PBL guidance to properly assess the relevance of those interviewee responses which supported CIP involvement:

‘To guide contractors to fix what is important to the government customer - reliability’

> CIP is not the only way to incentivize the contractor to improve reliability. PBL contracts are more profitable for the contractor when the engine stays ’on-wing’ and is not returned for maintenance. The investment in reliability improvements by the contractor are justified by these lower future costs.

‘CIP levels the competition or prolongs it (one side never too far from winning next competition round). It could be used to fund thrust or reliability depending on the situation’.

> Thrust is also closely bounded by JSF performance specifications and overall system boundaries (engine size, fuel consumption, engine inlet size, etc.). Initial reliability is specified and part of the engine qualification process. The contractor would improve thrust or reliability to compete for a greater share of the acquisition and to reduce support costs.

‘Contractor profit drives decisions for reliability not necessarily safety’.

> By including periods of safe operation as a factor in the competition, the contractor becomes incentivized to meet safety requirements as well as reliability.

E. CHAPTER SUMMARY

Many lessons learned have been gleaned from the interviews with the veterans of the first engine war and are invaluable for guiding the next great engine war. The interviews were structured to gather perspectives and guidance from the stakeholders of the subject engine competition. Studies of the organizational structure through the ‘cultural’ and ‘political lenses’ were helpful to properly frame the responses.

Overall, a consensus among interviewees was that engine competition is a good thing and certainly resulted in improved responsiveness at P&W. The negative impacts to competition centered on supportability and the competition criteria not necessarily tied to actual product performance. The competition criteria need to include acquisition costs *and* support costs to properly incentivize improved product reliability investments. Foreign Military Sales (FMS) can extend competition past the US Government acquisition period, but FMS must be balanced in the competition equation and included in supportability planning.

Lastly, the CIP participation by JSF is obviated by the forces of competition and PBL. The performance based logistics and competition factors will encourage the competitors to improve their baseline product reliability without the Government funding additional testing and analysis. The Great Engine War competition produced design improvements from both P&W and GEAE.

V. CONCLUSIONS AND RECOMMENDATIONS

A. CONCLUSIONS

A thorough analysis of the ‘Great Engine War’ literature and interviews with stakeholders has yielded the following conclusions which are useful for any program to guide their competition strategy:

1. Propulsion System Competition is Highly Advantageous When the Procurement is Relatively Large

This is due to the market entry and exit barriers inherent in the aircraft engine business. Systems procured for low quantity fleets (the B-2 *Spirit* F117 engine for example) simply can’t justify the approximately doubled development cost for an alternate engine for competition. Each new system must perform the analysis based on its unique situation (Hoover, 1986).

2. Competition Should Be Continued On a Recurring Basis for as Long as Possible to Derive the Maximum Benefit

Interview responses suggest this is admittedly difficult and requires a balanced competition among approximately equal competitors continually vying for an increased portion of the market. The ‘level playing field’ must be maintained by not overtly or covertly rewarding higher thrust performance. If one competitor is consistently losing, their mediocre performance is tacitly rewarded by a steady contract and guaranteed (if admittedly smaller) profits…

3. Avoid a ‘Winner Takes All’ Mentality

Each competitor needs to be awarded a yearly minimum buy amount sufficient to keep a viable production line open to respond to future competition.

4. Plan for Competition from the Outset

Perform the analysis early in the acquisition process to determine if competition of the system or sub-system is justified. The value of positive impacts to reliability and assurance (through competition) of the lowest possible acquisition and support costs should be considered. Design the system for complete commonality for either competed sub-system. Specify in the requirements document a single support system (to include common support equipment, information handling, training, and technical data formats).

5. Plan for Performance Based Logistics for Sustainment

Under PBL each contractor will be incentivized to keep driving lower the government cost for Operations and Maintenance. Legacy systems such as the F-16, pay the contractors for parts and equipment to repair failed components. Under PBL, the contractor is paid on a cost/operating hour basis. If the aircraft system doesn't fail – the contractor enjoys 100% profit. The contractor is guided by profit and a reliable system is more profitable. The contractor can easily justify investing in engineering efforts to fix reliability degraders (Defense Acquisition University, 2005).

B. RECOMMENDATIONS

To specifically guide the Joint Strike Fighter propulsion system acquisition and manage the competition between P&W and GEAE/RR, the JSF Program Office should carefully consider the following recommendations:

1. Strictly Adhere To Airframe Commonality for Either Propulsion System

The long lead time and basing considerations required by a unique airframe for each propulsion system would only complicate the competition process and yield less-than optimal results (Camm, 1993). To help level the acquisitions, and yet retain deploying F-35s as whole fighting units, the JPO

should consider letting only the training site squadrons (which usually do not deploy) be equipped with both F135 and F136-powered aircraft (if necessary to balance the acquisition numbers of F135s and F136s resulting from competition).

2. Competition Criteria Must Include Supportability Costs

By keeping PBL sustainment as competition criteria, the contractor will be incentivized to reduce acquisition cost and sustainment costs (Defense Acquisition University, 2005).

3. Do Not Pursue a Warranty Strategy

From the interviews and PBL guidance, the warranty and its associated cost is rendered obsolete. Poor engine performance would cost the contractor sales in future competitions.

4. Plan for Competition On An Annual Basis

Each competition cycle is an opportunity for the competitors to further refine and reduce the cost of their proposals. By extending the competition for as long as practicable, the maximum benefit to the government is realized (Ogg, 1987).

5. Maintain A Concerted Effort To Encourage Both Competitors To Attempt To Win The Maximum Share

Emphasize the continuing government requirement for contractor-provided PBL sustainment even after production ceases. The supplier of the majority of the operating fleet will also enjoy the lion share of the sustainment funding for the rest of the program. This should keep one competitor from being satisfied with a small, albeit guaranteed, business.

6. Do Not Participate In the Component Improvement Program (CIP)

From the interviews and DoD guidance, the competition and PBL will drive the contractors to produce a more robust design and to rapidly react to reliability problems. The only other reason to apply for CIP funding is to help failing competitors boost reliability and thus remain competitive. This charitable act would work to disincentive both contractors to emphasize robust design elements.

C. SUMMARY

The conclusions could help guide future programs considering the competition for acquisition of sub-systems. The proper assessment of possible candidates relies primarily on quantity. The competed systems require careful planning for interchangeability and support system commonality.

The recommendations should provide some guidance as the acquisition for JSF propulsion systems continues through the next decade.

LIST OF REFERENCES

Ancona, Kochan, Scully, Van Maanen, & Westney. (1999). *Organizational Behavior & Processes* (Module 2, p. 7). Cincinnati, Ohio: South-Western College Publishing.

Baugher. (2000). *Engines for the General Dynamics F-16 Fighting Falcon.* Retrieved July 6, 2005, from http://home.att.net/~jbaugher4/f16_6.html

Brannan, Liz. (2003). *Lockheed Martin's Evolving F-16 Maintains Warfighter's Edge in Modern Combat.* Retrieved July 11, 2005, from http://www.lockheedmartin.co.uk/news/158.html

Camm, Frank. (1993). *The Development of the F100-PW-220 and F110-GE-100 Engines: A Case Study of the Risk Assessment and Risk Management*. Santa Monica, California: RAND.

Chelimsky, Eleanor. (1991). *Using Structured Interviewing Techniques* (pp. 23 and 78). Washington, D.C.: Government Accounting Office.

Defense Acquisition University. (2005). *Performance Based Logistics: A Program Manager's Product Support Guide*. Fort Belvoir, Virginia: Author

Drewes, Robert W. (1987). *The Air Force and the Great Engine War* (pp. 98-100). Washington, DC: National Defense University Press.

Federation of American Scientists. (2005). Retrieved July 6, 2005, from http://www.fas.org/man/dod-101/sys/ac/jsf.htm

Fieser, Greg. (2003). *F-16 Fighting Falcon Production Block Designations*. Retrieved July 6, 2005, from http://www.habu2.net/vipers/viperblocks/

Global Security. (2005). *F-16 Fighting Falcon*. Retrieved July 6, 2005, from http://www.globalsecurity.org/military/systems/aircraft/f-16-history.htm

Hoover, Jeffery A. (1986). *Alternate Fighter Engines Competition Study* (p. 3). Wright-Patterson Air Force Base, Ohio: Air Force Systems Command.

JSF Public Affairs. (2003) *F135 Description*. Retrieved July 6, 2005, from http://www.jsf.mil/program/prog_org_propulsion.htm

JSF Public Affairs. (2003) *JSF History CALF*. Retrieved July 6, 2005, from http://www.jsf.mil/history/his_prejast.htm#CALF

Leginus, Brian R. (1998). *Fighter Engine Competition: A Study of Factors Affecting Unit Price* (p. 22). ANSER.

Mayes, Victoria. (1988). *Analysis of the Air Force and the Great Engine War*. Wright-Patterson Air Force Base, Ohio: Air Force Institute of Technology

Nagy Hesse-Biber, Sharlene & Levy, Patricia. (2004). *Approaches to Qualitative Research A Reader on Theory and Practice*. New York: Oxford University Press.

Nahmias, Steven. (2001). *Production and Operations Analysis* (4th ed.). Boston, MA: McGraw-Hill Irwin.

Nederveen, Gilles, Van, Captain (USAF). (2000). *The F-16 Block 60: A High-Tech Aircraft for a Volatile Region*. Retrieved July 6, 2005, from http://www.airpower.maxwell.af.mil/airchronicles/apj/apj00/fal00/phifal00.htm

Ogg, Jon Steven. (1987). *Metamorphosis of Business Strategies and Air Force Acquisition Policies in the Aerospace Propulsion Industry: Case Study of the "Great Engine War"*. Massachusetts: Massachusetts Institute of Technology.

Schinasi, Katherine. (2003). *Joint Strike Fighter Acquisition Cooperative Program Needs Greater Oversight to Ensure Goals Are Met* (pp. 10, 11, 111). Government Accounting Office.

Wikipedia. (2005). *Learning Curve Example*. Retrieved July 6, 2005, from http://en.wikipedia.org/wiki/Learning_curve#Examples

Younossi, O., Arena, M., Moore, R., Lorell, M., Mason, J., & Grasser, J. (2002). *An Overview of Military Jet Engine History* (Appendix B). RAND. Retrieved July 6, 2005, from http://www.rand.org/publications/MR/MR1596/MR1596.appb.pdf

INITIAL DISTRIBUTION LIST

1. Defense Technical Information Center
   Ft. Belvoir, Virginia

2. Dudley Knox Library
   Naval Postgraduate School
   Monterey, California

3. Prof. Walter Owen
   Naval Postgraduate School
   Monterey, California

4. Al Bodnar
   Secretary of The Air Force/XCOSM
   Washington, DC

5. Sonny Fann
   Naval Air Warfare Center – Aircraft Division
   Patuxent River, Maryland

6. Denny Barr
   Naval Air Warfare Center – Aircraft Division
   Patuxent River, Maryland

7. Stoney MacAdams
   Joint Strike Fighter Program/Propulsion Acquisition
   Arlington, Virginia

8. Karl Amick
   Office of the Under Secretary of Defense/Logistics, Plans, and Programs
   Washington, DC